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13. ABSTRACT (Maximum 200 words)  During the period June 1, 1991, through May 31, 1995 seven monographs on the physics of ice were written and printed: <ol style="list-style-type: none"> <li>1. The Structure of Ordinary Ice. Part I: Ideal Structure of Ice.</li> <li>2. Defects in Ice. Part I: Point defects.</li> <li>3. Defects in Ice. Part II: Dislocations and Plane Defects.</li> <li>4. Electrical properties of ice: Part I. Conductivity and Dielectric Permittivity of Ice. Part II. Advanced Topics and New Physical Phenomena.</li> <li>5. The Surface of Ice.</li> <li>6. Electromechanical Phenomena in Ice.</li> <li>7. Optical Properties of Ice.</li> </ol> <p>These monograph number 646 pages including 221 figures and 850 references. The lists of the monographs contents is in the Appendix. All the monographs of the series passed through intensive national and international review and were very well accepted by scientists and engineers working on ice. <b>Eighth monograph</b> entitled Photoelectric and Photoplastic Effects in Ice will be finished soon.</p>					
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**A BOOK AND SERIES OF MONOGRAPHS ON ICE PHYSICS**

**FINAL REPORT**

**VICTOR F. PETRENKO**

**JULY 7, 1995**

**U. S. ARMY RESEARCH OFFICE**

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## STATEMENT OF THE PROBLEM

At present, many thousands of people around the world deal with ice, snow, and permafrost. They include basic and applied scientists, engineers, navigators, meteorologists and others. While just a small number of these people makes a contribution to basic Ice Physics, all of them use, more or less frequently, knowledge from it. Moreover, much successful applied research is based on fundamental science. This is just one reason for ice specialists to have an up-to-date textbook on Ice Physics on their desks.

Several times in the past this kind of book was produced. First it is necessary to mention Fletcher's book on "The Chemical Physics of Ice" [1]. Fletcher designed his book in a typical textbook format: it is reasonably brief and easy to understand. He touched on a few of the most important topics, but not all of them. The most complete and fundamental book of Ice Physics was written by Hobbs [2], in which he considered almost all aspects of the basic knowledge of ice known in 1972. Another work was subsequently written by John Glen in 1974 [3]. He wrote briefly and clearly and reviewed almost all subjects. This work (two monographs) was (and in some respects still is) a magnificent introduction to ice. Finally, Maeno wrote (in Japanese) a simple popular book [4] the purpose of which was to attract people's attention to the subject.

All of these are now out of date. During the past twenty years a significant amount of new experimental and theoretical work has appeared, to the extent that our views on Ice Physics have dramatically changed. New areas of research have opened up based upon recent discoveries. Intensive studies in physics, chemistry and the mechanics of ice have resulted in the formulation of physical laws using simpler and more direct ways; we have discovered that some of the physical models previously used were incorrect. So, we may now say that the Physics of Ice is a much better understood subject than it was twenty years ago. A list of particular achievements and discoveries in ice research was included in the first proposal.

These reasons explain the need for a new book on ice physics. The Principal Investigator was given a contract from ARO and US Army CRREL to produce such a book and began this work in June 1991.

## SUMMARY OF THE MOST IMPORTANT RESULTS

During the period June 1, 1991, through May 31, 1995 seven monographs on the physics of ice were written and printed:

1. The Structure of Ordinary Ice. Part I: Ideal Structure of Ice.
2. Defects in Ice. Part I: Point defects.
3. Defects in Ice. Part II: Dislocations and Plane Defects.
4. Electrical properties of ice:
  - Part I. Conductivity and Dielectric Permittivity of Ice.
  - Part II. Advanced Topics and New Physical Phenomena.
5. The Surface of Ice.
6. Electromechanical Phenomena in Ice.
7. Optical Properties of Ice.

These monographs number 646 pages including 221 figures and 850 references. The lists of the monographs contents is in the Appendix. All the monographs of the series passed through intensive national and international review and were very well accepted by scientists and engineers working on ice. **Eighth monograph** entitled Photoelectric and Photoplastic Effects in Ice will be finished soon.

P. I. was simultaneously working on the united book on Ice Physics. This work is mostly accomplished and proposals were sent to four publishing houses : Oxford University Press, Cambridge University Press, Taylor & Francis and IOP. Oxford University Press and Taylor & Francis have finish the proposal evaluation are ready to sing a contract. Cambridge University Press and IOP will reply by October 1.

Below are the contents of these eight monograph:

# **1. THE STRUCTURE OF ORDINARY ICE Ih. PART I : IDEAL STRUCTURE OF ICE**

1. INTRODUCTION
2. CHEMICAL CONTENT OF WATER AND ICE
3. WATER MOLECULES IN VAPOR, WATER AND ICE
4. NATURE AND PROPERTIES OF HYDROGEN BONDS,
5. PHASE DIAGRAM OF WATER AND PHASE TRANSITIONS
6. STRUCTURE OF ORDINARY ICE IH. POSITIONS OF OXYGEN ATOMS
7. STRUCTURE OF ICE IH. ARRANGEMENT OF PROTONS AND CONFIGURATIONAL ENTROPY OF ICE.
8. ELECTRONIC STRUCTURE OF ICE.

## **2. DEFECTS IN ICE. PART I. POINT DEFECTS**

PREFACE

INTRODUCTION

NOMENCLATURE

GENERAL CONSIDERATION OF POINT DEFECTS

MOLECULAR DEFECT

PROTONIC DEFECTS

STATISTICS OF PROTONIC POINT DEFECTS IN ICE

ELECTRICAL PROPERTIES OF PROTONIC DEFECTS

ACTIVATION VOLUME OF PROTONIC DEFECTS

ATOMIC STRUCTURE OF PROTONIC DEFECTS

IMPURITIES

ELECTRONIC DEFECTS

FIGURES CAPTIONS

BIBLIOGRAPHY

## **3. DEFECTS IN ICE. PART II. DISLOCATIONS AND PLANE DEFECTS**

PREFACE

1 INTRODUCTION

2. DISLOCATIONS IN THE ICE STRUCTURE

2.1 Basal dislocations

2.2 Non-basal dislocations

3. DIRECT OBSERVATION OF DISLOCATIONS

3.1 General

3.2 The X-ray topography technique

3.3 Grown -in dislocations

3.4 Dislocations associated with plastic deformation

4. DISLOCATION MOBILITY

4.1 Experimental observations

4.2 The Peierls model for basal dislocations

4.3 Proton disorder

5. THE ROLE OF DISLOCATIONS IN THE PLASTIC DEFORMATION OF SINGLE CRYSTALS

5.1 Pure crystals

5.2 Doped crystals and electrical effects

6. STACKING FAULTS

6.1 The structure of stacking faults in ice

6.2 Observations of stacking faults

7. GRAIN BOUNDARIES

7.1 Structure

7.2 Electrical properties of grain boundaries in doped ice

FIGURE CAPTIONS

REFERENCES

## 4. ELECTRICAL PROPERTIES OF ICE

PREFACE

NOMENCLATURE

### PART I CONDUCTIVITY AND DIELECTRIC PERMITTIVITY OF ICE

1. INTRODUCTION
2. THE NATURE OF ELECTRIC CHARGE CARRIERS IN ICE
3. JACCARD'S MODEL OF ELECTRICAL PROPERTIES OF ICE. INFINITE SIZE
  - 3.1 PROTONIC CHARGE CARRIERS
  - 3.2 ELECTRICAL PROPERTIES. ONE TYPE OF CHARGE CARRIER
  - 3.3 OTHER CHARGE CARRIER TRANSFERS AND THEIR EFFECTIVE CHARGES
  - 3.4 GENERAL CONSIDERATION OF JACCARD'S MODEL WITH FOUR KINDS OF CARRIERS
  - 3.5 ANALYSIS OF JACCARD'S RESULTS
4. ELECTRICAL PROPERTIES OF ICE OF FINITE SIZE
  - 4.1 LOW-FREQUENCY, LIMIT-SCREENING LENGTHS
  - 4.2 FREQUENCY DEPENDENCE OF DIELECTRIC PERMITTIVITY
5. CONCENTRATION OF CHARGE CARRIERS
  - 5.1 INTRINSIC CHARGE CARRIERS
  - 5.2 SUPERIONIC TRANSITION AND THE SUPERIONIC STATE OF ICE
  - 5.3 PROTONIC CHARGE CARRIERS INTRODUCED BY DOPING
6. EXPERIMENTAL TECHNIQUES FOR INVESTIGATION OF CONDUCTIVITY AND DIELECTRIC
  - 6.1 MEASURING CIRCUITS
  - 6.2 ELECTRODES
  - 6.3 SURFACE CONDUCTIVITY AND GUARD RINGS
  - 6.4 THE INFLUENCE OF INHOMOGENEITY ON THE FREQUENCY DEPENDENCE OF ICE
7. REVIEW OF EXPERIMENTAL RESULTS ON ICE CONDUCTIVITY AND DIELECTRIC PERMITTIVITY
  - TABLE I
  - TABLE II
  - TABLE III

## ELECTRICAL PROPERTIES OF ICE, PART II

### ADVANCED TOPICS AND NEW PHYSICAL PHENOMENA

9. RELAXATION TIMES OF ELECTRIC POLARIZATION AND ELECTRIC FIELDS IN ICE
10. RECOMBINATION INJECTION OF IONS INTO ICE
11. RECOMBINATION EXTRACTION OF CHARGE CARRIERS FROM ICE
12. PROTON INJECTION FROM PD ELECTRODES INTO ICE
13. FIELD ACTION TRANSISTOR MADE OF ICE
14. "CROSSOVER" IN THE DIELECTRIC PERMITTIVITY OF ICE
15. THERMALLY STIMULATED DEPolarIZATION

CONCLUSION

REFERENCES

FIGURE CAPTIONS

## 5. ICE SURFACE

### NOMENCLATURE

### INTRODUCTION

### PART I. EXPERIMENTAL RESULTS ON THE STRUCTURE AND PROPERTIES OF ICE SURFACE

- X-ray diffraction
- Proton Channeling
- Optical Ellipsometry
- Nuclear Magnetic Resonance (NMR)
- Electrical conductivity of ice surface
- Surface Charge and Surface Potential
- Surface electrochemical potential
- Photoemission of electrons from the ice surface
- Surface optical absorption in infrared region
- Regelation (refreezing), sintering and adhesion
- Absorption of gasses on the ice surface
- Surface Energy
- Summary of main experimental results
  - The existence of a special layer
  - The thickness of the layer and the domain of its existence
  - Molecular structure of the layer
  - Physical properties of the layer as compared with water and ice

### PART II. THEORETICAL MODELS OF ICE SURFACE

### BIBLIOGRAPHY

### FIGURE CAPTIONS

### FIGURES

## 6. ELECTROMECHANICAL PHENOMENA IN ICE

### NOMENCLATURE

### INTRODUCTION

### ELECTRICAL PHENOMENA IN ICE FRICTION

- The structure and electrical properties of ice surface
- Early works, asymmetric rubbing
- Frictional electrification
- Effect of electric fields on ice friction

### ELECTRO ELASTIC EFFECTS

- Is ice piezoelectric?
- Phonon induced polarization of ice
- Polarization induced by non uniform strain
- Other pseudo piezoelectric effects

### ELECTROMAGNETIC PHENOMENA IN ICE FRACTURE

- Electromagnetic emission from cracks in ice
  - Theory
  - Laboratory experiments
  - Field experiments

### PHENOMENA ASSOCIATED WITH MOTION OF CHARGED DISLOCATIONS

- Dislocation currents in ice
- Action of electric field on plastic deformation
- Motion of dislocations in electric fields
- Effect of static electric field on ice creep
- Action of plastic deformation on electrical properties of ice

### BIBLIOGRAPHY

## FIGURE CAPTIONS FIGURES

### 7. OPTICAL PROPERTIES OF ICE

PREFACE  
INTRODUCTION  
NOMENCLATURE  
DEFINITIONS  
DIELECTRIC PERMITTIVITY OF ICE FROM SONIC TO X-RAY FREQUENCY  
ANISOTROPY AND BIREFRINGENCE OF ICE IH  
ABSORPTION AND REFLECTION OF ULTRAVIOLET LIGHT  
ABSORPTION AND REFLECTION OF INFRARED LIGHT.  
RAYLEIGH SCATTERING OF ICE  
RAMAN SCATTERING  
PHOTOLUMINESCENCE  
LUMINESCENCE UNDER ACTION OF HIGH ENERGY PARTICLES  
THERMOLUMINESCENCE  
TRIBOLUMINESCENCE  
BIBLIOGRAPHY  
FIGURE CAPTIONS  
FIGURES

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### 8. PHOTOELECTRIC AND PHOTOPLASTIC EFFECTS IN ICE

PREFACE  
INTRODUCTION  
NOMENCLATURE  
INTRINSIC PHOTOCONDUCTIVITY OF ICE  
IMPURITY PHOTOCONDUCTIVITY OF ICE  
LIFE TIME OF NONEQUILIBRIUM CHARGE CARRIERS IN ICE  
NATURE OF PHOTO-CHARGE CARRIERS IN ICE  
ELECTROMOTIVE FORCE  
ELECTRO-OPTICAL EFFECTS AT ICE-SEMICONDUCTOR INTERFACES  
POSSIBILITY OF ICE SOLAR CELLS  
PHOTOPLASTIC EFFECT IN ICE  
BIBLIOGRAPHY  
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FIGURES

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2. Hobbs, P. V. (1974) "Ice Physics," 837p., Clarendon Press, Oxford
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